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APPLICATION OF POLARIMETRIC-INTERFEROMETRIC PHASE COHERENCE OPTIMIZATION (PIPCO) PROCEDURE TO SIR-C/X-SAR TIEN-SHAN TRACKS 122.20 (94 Oct. 08)/154.20 (94 Oct. 09) REPEAT-ORBIT C/L-BAND POL-D-InSAR IMAGE OVERLAYS WITHIN THE 'KUDARA POLYGON' OF RAS-SD-BNSC, ULAN UDE, BURIATIA/RUSSIA

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Abstract: During the past decade, Radar Polarimetry has established itself as a mature science and advanced technology in high resolution POL-SAR imaging, image target characterization and selective image feature extraction. More recently, with the addition of single platform dual antenna interferometers, digital elevation mapping (DEM) was made possible which though can be recovered in most cases equally well from standard fully polarimetric POL-SAR image data utilizing the Schuler purely polarimetric DEM algorithms not requiring an interferometer. However, in order to be able to fully describe direction-sensitive environmental stress changes, it is necessary to rapidly advance repeat-pass (RP) fully polarimetric (POL: Scattering Matrix) Differential (D) Interferometric (In) SAR imaging systems (RP-POL-D-InSAR) which have emerged with the successful SIR-C/X-SAR Missions 1 (1994 April)/2 (1994 October). In pursuing this goal, Shane R. Cloude in addition to introducing the Polarimetric Entropy/Anisotropy Method together with Eric Pottier, more recently achieved another milestone by introducing the Polarimetric-Interferometric Phase Coherence Optimization (PIPCO) procedure together with Kostas P. Papathanassiou. This PIPCO procedure is verified in this paper by utilizing an ideally matching repeat-pass pair of the recent SIR-C/X-SAR Mission 2, Tien-Shan Tracks within the Russian Academy of Sciences, Siberian Division, Buriat Natural Science Center (RAS-SD-BNSC) SE Baikal Lake, Selenga Delta (Kabansk-Kudara-Oymur: N52.16°, E106.67°) Geo-environmental Sanctuary, the 'Kudara Polygon' for which various institutes of RAS-SD-BNSC have collected extensive geographic (geo-ecological and geo-tectonic) environmental information and vegetative groundtruth data over the past several decades. This tectonically highly active region lies within the Mid-Asian Baikal Tectonic Rift Zone of the Hövsögöl-Baikal Lakes Basin which was recently declared as a World Heritage Site.

Recommendations: The very impressive application of the PIPCO algorithm of Cloude-Papathanassiou to these combined data sets proved the merits and definite need for rapidly advancing fully polarimetric SAR interferometry, i.e., enabling unsupervised RP-POL-D-InSAR environmental stress change imaging. In essence this important pilot study proves why it would have been highly desirable for the forthcoming SIR-C/X-SAR Mission 3 (SRTM: C/X) to become fully polarimetric; and especially why all future air/space-borne InSAR systems ought to become fully polarimetric POL-D-InSAR imaging platforms, and why we require multi(hyper-spectral)band POL-D-SAR systems to perform within the entire VHF-EHF (100MHz to 10GHz) spectral region in order to accomplish complete direction-sensitive in-depth focused geo/eco-environmental stress change imaging. In addition, we here recommend that the entire Hövsögöl/Mongolia - Baikal/Buriatia Lakes Basin, containing the Mid-Asian Tectonic Rift Zone, be declared a permanent air/space-borne SAR imaging test site for ongoing SAR imaging and future RP-POL-D-InSAR imaging missions.

I. BACKGROUND ON POLARIMETRIC INTERFEROMETRIC PHASE COHERENCE OPTIMIZATION (PIPCO) PROCEDURES OF CLOUDE AND PAPATHANASSIOU

Radar/SAR interferometry has become an important tool in space and air-borne remote sensing of geo-environmental stress changes because of its capabilities of providing all weather, day and night, high resolution digital elevation maps (DEMs) of terrain. However, the quality of these maps is critically dependent on the coherence between multiple images, and this in turn depends on several factors, including geometrical and temporal decorrelations [1] such as those generated by statistical fluctuations in the surface and/or volume scattering mechanisms. Recently, Cloude and Papathanassiou [2] introduced another highly relevant 'Polarimetric Optimization Algorithm in Radar (SAR) Interferometry' which greatly improves the quality of the interferograms -- provided fully coherent polarimetric scattering matrix SAR data have been collected. This algorithm builds on the polarimetric entropy/anisotropy algorithm developed by Cloude and Pottier [3] based upon a fully coherent vector wave scattering theory and is extended to a scattering vector formulation of polarimetric interferometry and expressed for the symmetric coherent scatter case by the scattering feature vector

$$\mathbf{k} = [S_{HH} \quad \sqrt{2}\, S_{HV} \quad S_{VV}]^T \tag{1a}$$

or equivalently

$$\mathbf{k} = \mathrm{Trace}([S]\psi_p) = 1/\sqrt{2}\,(S_{HH} + S_{VV} \quad S_{VV} - S_{HH} \quad 2S_{HV})^T, \tag{1b}$$

where ψ_p are the set of 2×2 complex Pauli basis matrices [3]. Under a change of scattering basis, **k** transforms into $\mathbf{k}' = [U_3]\mathbf{k}$ via a 3×3 complex unitary matrix [U]. By interfering two images I1 ($\mathbf{k}_1$) and I2 ($\mathbf{k}_2$), two of the true hermitian products $[T_{11}] = \langle \mathbf{k}_1 \mathbf{k}_1^{*T} \rangle$ and $[T_{22}] = \langle \mathbf{k}_2 \mathbf{k}_2^{*T} \rangle$ represent the standard 3×3 hermitian covariance matrices for separate images [3], whereas the third 3×3 complex matrix $[\Omega_{12}] = \langle \mathbf{k}_1 \mathbf{k}_2^{*T} \rangle$ represents the non-hermitian interferometric phase correlation matrix, where a single 6×6 hermitian matrix

$$[T_6] = \left\langle \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} \begin{bmatrix} k_1^{*T} & k_2^{*T} \end{bmatrix} \right\rangle = \left\langle \begin{bmatrix} T_{11} & \Omega_{12} \\ \Omega_{12}^{UT} & T_{22} \end{bmatrix} \right\rangle \tag{2}$$

represents the generalized polarimetric-interferometric coherence matrix [2]. By introducing two unitary complex vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ describing two vector scattering mechanisms associated with $\mathbf{k}_1$ and $\mathbf{k}_2$, respectively; two associated scalars are obtained defining the complex scattering coefficients $\mu_1 = \mathbf{w}_1^{*T}\mathbf{k}_1$ and $\mu_2 = \mathbf{w}_2^{*T}\mathbf{k}_2$, so that the generalized polarimetric formulation of the '**Interferometric Coherence Coefficient:** Λ' becomes

$$\Lambda = \frac{|w_1^{*T} \langle [\Omega_{12}] \rangle w_2|}{\left\{ \langle w_1^{*T} [T_{11}] w_1 \rangle \langle w_2^{*T} [T_{22}] w_2 \rangle \right\}^{1/2}} \tag{3}$$

The '**Interferometric Coherence Optimization**' procedure is outlined in [4], where the Langrangian function

$$L = w_1^{*T}[\Omega_{12}]w_2 + \lambda_1\left(w_1^{*}[T_{11}]w_1 - 1\right) + \lambda_2\left(w_2^{*}[T_{22}]w_2 - 1\right) \tag{4}$$

needs to be optimized ($\partial L/\partial \mathbf{w}_1^{*T} = 0$! and $\partial L/\partial \mathbf{w}_2^{*T} = 0$!) resulting into three real eigenvalues ($\lambda_1 \lambda_2^*$) so that the optimum value of L corresponds to the maximum value $\lambda_1 \lambda_2^*$ as discussed in [2] and [4].

Similar to applying the polarimetric target decomposition theory directly to $[T_{11}]$ or $[T_{22}]$ for developing the polarimetric entropy/anisotropy method [3,6], Cloude together with Papathanassiou also introduced the '**Interferometric Phase Decomposition**' method [5] which greatly assists in highlighting the importance of polarimetric interferometric phase description. In Cloude and Pottier [3,6], it is shown that the hermitian covariance matrix $<[T_{ii}]>$, i.e., $<[T_{11}]>$ or $<[T_{22}]>$, can be used to yield a basis invariant decomposition into orthogonal scattering processes via

$$<[T]> = [U_3]<[\Sigma]>[U_3]^{-1} = \sum_{i=1}^{3} \lambda_1 e_i e_i^{*T} \tag{5}$$

where $[\Sigma]$ is a 3×3 diagonalized matrix with the eigenvalues λ_1 of $<[T]>$; and the diagonalization matrix $[U_3]$ has as columns the complex eigenvalue λ_2 of $<[T]>$. The physical interpretation of each scattering component is related with its corresponding eigenvectors and their relative contribution is given by the appropriate eigenvalue which when further extended leads to the polarimetric entropy and anisotropy approaches discussed in [3,6]. Based on the coherence optimization algorithm, this concept can now be extended and applied directly to the phase of the interferograms between scattering coefficients related to the same or different scattering mechanisms in the two primary images I1and I2 by projecting the scattering vectors, $\mathbf{k}_1$ and $\mathbf{k}_2$ onto the corresponding singular vectors $\mathbf{w}_i$ and $\mathbf{w}_j$, so that

$$[T_{11}]^{-1}[\Phi_{12}][T_{22}]^{-1}[\Phi_{12}]^{*T} = \sum_{i=1}^{3} (\lambda_1 \lambda_2^*)_i w_i w_i^{*T} \tag{6a}$$

$$[T_{22}]^{-1}[\Phi_{12}]^{*T}[T_{11}]^{-1}[\Phi_{12}] = \sum_{j=1}^{3} (\lambda_1 \lambda_2^*)_j w_j w_j^{*T} \tag{6b}$$

with

$$\mu_1 \mu_2^* = (w_i^{*T} k_1)(w_j^{*T} k_2) \tag{6c}$$

and the polarimetric interferometric phase of the interferograms is then given by

$$\phi_{ij} = arg(\mu_1 \mu_2^*) = arg(w_i^{*T} k_1 k_2^{*T} w_j) \tag{7}$$

which defines the basis of the Polarimetric Phase Spectral Decomposition method introduced in [5].

There still exist several unresolved basic questions currently under investigation by Konstantinos P. Papathanassiou and Shane R. Cloude such as for example the unique definition of absolute phase where in [5] it is proposed that $\arg(e_i e_j^*) = 0$ by conjecturing that the polarimetric interferometric phase is contained in the vectors $\mathbf{k}_1$ and $\mathbf{k}_2$. It should be noted here that the polarimetric-interferometric phase spectral decomposition method will allow for identifying differential directive ground pattern changes such as that of vegetation height and transverse (branches) extent, biomass, etc., as well as of tectonic stress surface-texture changes (lateral, vertical and skewing).

The '**Interferometric Coherence Coefficient Λ**' defined in eq.(3), derived by Cloude and Papathanassiou in [2], provides the basis for developing '**Vector (Polarimetric) Differential Interferometry**' in that the non-hermitian differential phase matrix $[J_{diff}]$ between two vector scattering processes $\mathbf{w}_1$ and $\mathbf{w}_2$ may be defined by

$$\left[J_{diff}\right] = <XX^{*T}> \qquad with \qquad X = \begin{bmatrix} w_1^{*T}\left[\Omega_{12}\right]w_1 \\ w_1^{*T}\left[\Omega_{12}\right]w_2 \end{bmatrix} \tag{8}$$

resulting in the polarimetric phase difference ϕ_{eff} of the vector differential interferograms

$$\phi_{eff} = arg\left\{\left(w_1^{*T} <\left[\Omega_{12}\right]> w_1\right)\left(w_1^{*T} <\left[\Omega_{12}\right]> w_2\right)^{*T}\right\} \tag{9}$$

which corresponds to the spatial separation of the vector scattering center w_1 relative to w_2 as was described in detail in [2,4,5]. As shown in [5], both interferograms have the same baseline so that the differential interferogram results directly from phase subtraction in the complex plane avoiding baseline induced errors however requiring sufficiently high coherence between w_1 and w_2. The coherence optimization algorithm can be used in order to find these w_1 and w_2 which possess a sufficiently high coherence, and in turn, can also be used for the formulation of differential interferograms as will be shown in Cloude and Papathanassiou [22].

In order to solve the polarimetric interferometric optimization and spectral decomposition methods, first a precise estimate of the generalized polarimetric-interferometric coherence matrix $[T_6]$ must be obtained from the "calibrated [S]" matrix data sets itself as discussed in [3] and further highlighted in [7]. In Chapter 5, Section 5.5 of [7], it is shown how the acquisition of the parameter estimates is obtained by N-look complex averaging

$$\left[T_{xx}\right] = \frac{1}{N}\sum_{i=0}^{N} k_x k_x^{*T} \qquad and \qquad \left[\Omega_{12}\right] = \frac{1}{N}\sum_{i=0}^{N} k_x k_y^{*T} \tag{10}$$

where the lower and upper bounds on N still need to be analyzed in depth and may depend strongly (i) on the particular scattering mechanism of a localized image scene, i.e., may vary strongly from flat to rugged vegetated hilly sections [7] as well as on (ii) Lee's polarimetric formulation of image speckle reduction based on Wishart distributions [19].

II. MEASUREMENT DATA ACQUISITION FOR DEMONSTRATING THE POLARIMETRIC-INTERFEROMETRIC PHASE COHERENCE OPTIMIZATION (PIPCO) PROCEDURE

First of all, in order to demonstrate the Polarimetric Entropy/Anisotropy and Spectral Decomposition theories, well calibrated fully polarimetric scattering matrix (calibrated - [S]) SAR systems are needed for satisfying stringent requirements on polarization purity, channel isolation and sidelobe reduction of the order of -33dB and better [7]. In the meantime, a rather impressive fleet of airborne multi-band and wideband polarimetric SAR (POL-SAR) systems has become available including the NASA-JPL AIR/TOP-SAR (P/L/C), the ERIM-IFSAR (C/X), the DLR E-SAR (P/L/C/X), the TNO-PHARRUS (L/X), the NAWC-ERIM QUAD-SAR (UWB: 200MHz - 900MHz, L/C/X), the MIT-LORRAL-SAR (Ku/Ka), etc., as catalogued in [8]. In addition, several airborne fully polarimetric interferometric (dual antenna) POL-InSAR systems have been realized by ERIM (IFSAR), NASA-JPL (AIR/TOP-SAR), DCRS (EMI-SAR), DLR (E-SAR), etc. [7] for which polarimetric-interferometric SAR image data processing will greatly benefit from the recent advances reported here. However, in order to apply the novel 'Polarimetric-Interferometric Phase Coherence Optimization Procedures' to high precision repeat-pass POL(In)-SAR image interferometry for delineating environmental stress changes (including tectonic deformation and battlefield scenarios, etc.) flight-stable platforms are required which at the current state-of-the-art in DGPS-INU flight pass precision control systems can best be realized by spaceborne POL-SAR imaging systems. Hitherto, however, no such spaceborne imaging systems except for the SIR-C/X-SAR Mission 1 (1994 April) and Mission 2 (1994 October) were realized; and only during Mission 2 (1994 October) was truly satisfactory repeat-pass D-POL-SAR Interferometry made possible. It is regrettable that for the forthcoming SIR-C/X-SAR Mission 3 (SRTM) **fully polarimetric (scattering matrix [S])**, dual interferometric antennas were ruled out for cost-saving (including limits on image storage and handling capacity on board of the space-shuttle), which may hamper progress for years (decades) to come. Indeed, we require fully polarimetric, multiband interferometric SAR imaging systems in order to be able not only to image the three-dimensional planetary surface profiles, but to detect, recognize and precisely identify vegetative growth and tectonic stress changes patterns in vertical and lateral extent. Furthermore, ideally we require POL-D-InSAR systems operating over a wide VHF - to - EHF hyper-spectral domain between about (100MHz to 10GHz, specifically within the entire L-band and upper P-band. This truly international multi-institutional collaborative effort merits full consideration for these urgent and timely requests.

After lengthy, careful screening of the SIR-C/X-SAR Missions 1/2 data files, Papathanassiou and Moreira [9] discovered that the repeat-orbit SIR-C/X-SAR Mission 2 provided -- among others -- at least one excellent L/C-band scattering matrix [S] pair for the Tien-Shan test site, extending via West Mongolia (Lake Hövsögöl) along the SE Baikal Lake through Buriatia into Yakutia (Lena River) in Siberia, etc., for data takes 122.20 (94 Oct. 08) and 154.20 (94 Oct. 09) as processed by NASA/JPL [10] (see map of Fig. 1a). Of specific interest are the Hövsögöl and Baikal-Selenga Delta image data sections in that the Inner-Asian Baikal Rift (which in about 1 million years may separate the Asian Continent into two separate ones) lies precisely within the pair of image swaths for data takes 122.20 - 154.20 [10] (see maps of Figs. 1b and 1c). By mere luck, Papathanassiou and Cloude [5] selected the section of this repeat-pass pair of most likely greatest tectonic as well as vegetative variance namely the Selenga Delta region extending north-east from Bojarsk → Bolshoye-Kolosovo/Kabansk → Kudara/Fotonovo → Oymur/ Selenginsk in Central West-Buriatia (appr. N 52.16°, E 106.67°), in the following designated as the 'KUDARA POLYGON' (see map of Fig. 1d). Here we note that the length of the chosen image data strip should be extended backwards (SW direction) by about 60km to include the entire SE Baikal shoreline, i.e., the `Saliv Cor' tectonic depression, plus about 60km in NE direction in order to include the fully forested mountain ranges beyond the Kama to the Burya rivers, tributaries to the Selenga river. This truly precious area [11] of rich forest and agricultural lands, scenically beautiful and tectonically very active region is well cartographed in a multi-disciplinary sense (tectonically [12], eco-environmentally [13], agricultural, forested [14], and aquatically [15]); and the Selenga delta serves as one of the main Siberian migrating bird and fishing sanctuaries -- in fact, the entire Hövsögöl-Baikal-Lake Basin was recently declared a world-heritage site and thus deserves special attention.

Listing of pertinent maps

Fig. 1a: SIR-C/X-SAR Mission 2 (Oct. 1994) Flight Paths with Identification of the Repeat-Pass Tien-Shan Tracks 122.20 (97 Oct. 08) and 154.20 (97 Oct. 09) over the Hövsögöl-Baikal Lake Basins of Mongolia - Buriatia

Fig. 1b: Visibility Extent of the Central Inner-Asia Mobile DLR Ulaan-Baatar/Mongolia Satellite SAR Image Data Down-Link Receiving Station (ERS-1/2, JERS/EROS) Covering the Entire Region of Interest

Fig. 1c: The Baikal Rift Zone: Distribution of Earthquake Epicenters and of the RAS-SD-BNSC Observing Station Network

Fig. 1d: The Baikal Lake - Selenga Delta SIR-C/X-SAR Repeat-Track 122.20/154.20 Polygon: The `Kudara Polygon'

In order to substantiate the repeat-pass pair (RPP) polarimetric (POL) differential (D) SAR interferometric (IN) image overlay (RP-POL-D-INSAR) results of Papathanassiou and Cloude [5], Boerner together with regional expert radio-geo-physicists (D.D. Darizhapov and B.Ch. Dorziev), radio-tectonologists (Y.B. Bashkuyev and G.I. Tatchkov), agro/eco-environmentalist (T.Kh. Tsybjitov) and aquatic-biologist (V.M. Korsunov) initiated a major geo-ecological groundtruth collection project under the ONR-WIPSS'96/97 program which is still ongoing [16]. Utilizing both the excellently recovered RP-POL-D-InSAR scattering matrix data sets of the NASA-JPL SIR-C/X-SAR Mission 2 data takes 122.20 and 154.20 provided by NASA-JPL, the polarimetric-interferometric SAR image data processing of Papathanassiou, and the Selenga-Delta groundtruth data acquisition of the RAS-SD-BNSC geo/eco-environmentalists; in the next Section, the algorithms, summarized in Section I, are applied and a preliminary comparative interpretation of results is provided by adding other polarimetric images for comparison purposes.

III. COMPARISON AND VERIFICATION OF POLARIMETRIC SINGLE PASS VERSUS REPEAT-PASS POLARIMETRIC-INTERFEROMETRIC CLASSIFICATION AND INTERPRETATION OF THE SIR-C/X-SAR MISSION 2 L/C-BAND DATA-TAKES, 1994 Oct. 08 (122.20) and Oct. 09 (154.20) USING EXISTING RP-D-POL-InSAR IMAGE PROCESSING ALGORITHMS

Utilizing all major existing polarimetric SAR image classification invariants, feature selection, entropy/

anisotropy and speckle reduction algorithms summarized in Chapter 5 of [17] including those of Krogager and Boerner [18], Cloude and Pottier [3,6], J-S. Lee et al. [19], Schuler et al. [20], and those most recently introduced by Cloude, Papathanassiou et al. [2,4,5,9,21], the single I1 (122.20) and I2 (154.20) versus repeat-pass RP-POL-InSAR images I12 are analyzed in depth for the "Kudara-Polygon" shown in Figs. 1 a/b/c/d.

3.1 Single pass polarimetric image I1 (122.20) versus I2(154.20) presentations

A complete set of false-color-coded images is presented as a basis for future comparison

a) **HV Basis Images**
Fig. 2L, L-band HV Basis Images (a. HH(L), b. HV(L), c. VV(L), d. SpHV(L))
Fig. 2C, C-band HV Basis Images (a. HH(C), b. HV(C), c. VV(C), d. SpHV(C))

b) **LR Basis Images**
Fig. 3L, L-band LR Basis Images (a. LL(L), b. LR(L), c. RR(L), d. SpLR(L))
Fig. 3C, C-band LR Basis Images (a. LL(C), b. LR(C), c.RR(C), d. SpLR(C))

c) **Krogager Pauli-Matrix Decomposition Images (see [18] for details)**
Fig. 4L, Pauli-Matrix Decomposition
Fig. 4C, Pauli-Matrix Decomposition
Fig. 5L, Left/Right-Helix Decomposition
Fig. 5C, Left/Right-Helix Decomposition

d) **Cloude-Pottier Polarimetric Entropy (H) vs Anisotropy (α) Images (see [3] and [5] for details)**
Fig. 6L, H - α Classification Maps
Fig. 6C, H - α Classification Maps

e) **Lee Speckle-Reduced Image Classification (see [19] and [23]**

Fig. 7L,	a. HH + VV	b. HH - VV	c. HV	d. Span HV
Fig. 7C	a. HH + VV	b. HH - VV	c. HV	d. Span HV

From a comparative inspection, we observe how the polarimetric image processing of either L or C band [S] matrix image data sets greatly improves on interpreting and classifying selective image features as will be discussed in a set of forthcoming papers prepared in collaboration with pertinent expert scientists of RAS-SD-BNSC at Ulan Ude, Buriatia for the specific 'Kudara-Polygon' under consideration. Most striking is the improvement of image clarity and quality that can be achieved with the implementation of the Lee speckle-reduction filter algorithm [19] which could serve as a standard data pre-processing tool of POL-SAR image data [22] from here on into the future! However, before introducing a systematic presentation of the RP-POL-D-InSAR image overlay interferograms; here, for completeness and for meaningful methodological comparisons the Schuler polarimetric method of constructing 3-D topographic Digital Elevation Maps (POL-3D-DEMs) directly from fully polarimetric ([S] matrix) SAR image data sets is presented first. In order to apply Schuler's POL-3D-DEM reconstruction method, the areal extent of the "Kudara Polygon" of Fig. 1d, originally chosen by Papathanassiou [5,21,23], was extended beyond the Saliv Cor (a land section that collapsed and sunk into Lake Baikal during the 1867 earthquake) in southwest backward-direction allowing one to establish proper boundary values for applying the Schuler algorithms [20,23].

f) **Schuler Polarimetric 3D Topographic DEMs**

Fig. 8L,	a. I1	b. I2
Fig. 8C,	a. I1	b. I2

We observe that the C-band POL-3D-DEMs are superior to the L-band POL-3D-DEMs and the slight differences between I1 and I2 profiles will be discussed separately.

3.2 Repeat-Pass Polarimetric Image Overlay Interferograms

A systematic presentation is given on a representative set of coherence histograms in the HV-basis, and LR-basis, for optimized coherence values for both the L and C bands clearly demonstrating that the phase coherence optimization in Polarimetric SAR interferometry provides superior results over using only a single HH, HV, VV; LL, LR, LL or in general arbitrary AA, AB, BB interferograms.

Fig. 9L Coherence Histograms: L-band
(a. Optimized Coherence Values b. HV-basis c. LR basis)

Fig. 9C Coherence Histograms: C-band
(a. Optimized Coherence Values b. HV-basis c. LR basis)

Fig. 10L L-band Eigenvalue Interferometric Coherence for Kudara Polygon, Buriatia
(a. 3rd Eigenvalue b. 2nd Eigenvalue c. 1st Eigenvalue)

Fig. 10C C-band Eigenvalue Interferometric Coherence for Kudara Polygon, Buriatia
(a. 3rd Eigenvalue b. 2nd Eigenvalue c. 1st Eigenvalue)

Fig. 11L L-band HV-Basis Interferometric Coherence for Kudara Polygon, Buriatia
(a. HH b. HV c. VV)

Fig. 11C C-Band HV-Basis Interferometric Coherence for Kudara Polygon, Buriatia
(a. HH b. HV c. VV)

Fig. 12L L-Band LR-Basis Interferometric Coherence for Kudara Polygon, Buriatia
(a. LL b. LR c. RR)

Fig. 12C C-Band LR-Basis Interferometric Coherence for Kudara Polygon, Buriatia
(a. LL b. LR c. RR)

Fig. 13L L-Band (HV-Basis) Magnitudes of Interferograms for Kudara Polygon, Buriatia
(a. HH b. HV c. VV)

Fig. 13C C-Band (HV-Basis) Magnitudes of Interferograms for Kudara Polygon, Buriatia
(a. HH b. HV c. VV)

Fig. 14L L-Band (LR-Basis) Magnitudes of Interferograms for Kudara Polygon, Buriatia
(a. LL b. LR c. RR)

Fig. 14C C-Band (LR-Basis) Magnitudes of Interferograms for Kudara Polygon, Buriatia
(a. LL b. LR c. RR)

Fig. 15L L-Band Interferometric Phase without Flat Earth Correction
(a. HH - HH b. HV - HV c. HH - VV d. LL - LL e. LR - LR f. LL - RR)

Fig. 15C C-Band Interferometric Phase without Flat Earth Correction
(a. HH - HH b. HV - HV c. HH - VV d. LL - LL e. LR - LR f. LL - RR)

Again, we observe that optimum interferometric coherence is obtained for the eigenvalue presentation as discussed in depth in forthcoming companion papers (see for example [22] and pertinent monographs of [23]) utilizing groundtruth information provided by pertinent experts from the RAS-SD-BNSC at Ulan Ude.

In order to carry out a complete comparative analysis of currently ongoing research on '**Repeat-Pass SAR Image Overlay Interferometry**', here the NASA-JPL techniques [24-26] pioneered by Richard Goldstein, Gilles Peltzer, Howard A. Zebker and Paul A. Rosen are most relevant (see pertinent Chapters 5 and 6 in [17]). A selective set of interferometric I12 Interferometric Phase Coherence images and of 3D Interferograms process desirably by Rosen and Peltzer would have been desirable which should include Figs. 16 L/C.

g) NASA-JPL Phase and Magnitude of Interferograms by Peltzer and Rosen

Fig. 16L
a. Int.Coh. (HH) b. Int.Coh. (VV)
c. Magn.Int. (HH) d. Magn.Int. (VV)
e. DEM HH f. DEM VV

Fig. 16C
a. Int.Coh. (HH) b. Int.Coh. (VV)
c. Magn.Int. (HH) d. Magn.Int. (VV)
e. DEM (HH) f. DEM (VV)

3.3 Differential Polarimetric-Interferometry

The polarimetric differential interferometric algorithms recently developed by Cloude, Papathanassiou and collaborators at DLR allow for precise calculations of Digital Elevation Maps and extraction of desirable height profiles. In addition, by digital differential phase coherence subtraction of the complex coherence values, it is also possible to discover differential vegetative growth changes (such as tree heights and directive transverse (branches) extent) or tectonic surface-texture stress changes which require extensive additional analyses subject to obtaining time-delayed (by days, weeks, months, years) sets of repeat-pass POL-D-InSAR image data take pairs. If the SIR-C/X-SAR Mission 3 (SRTM) could have been upgraded to include complete polarimetric antenna systems, this quest could have been answered in part. Certainly, the forthcoming LIGHT-SAR and ECHO-SAR systems design changes ought to satisfy the need for acquiring such complete polarimetric single and repeat-pass interferometric POL-D-InSAR image data sets not only for C- and X-band, but more so for spectral lines in the L-band and throughout the P-bands, say between 100MHz to 10GHz at least.

Utilizing the available POL-D-InSAR scattering matrix image data sets I1, I2 and I12 for the Kudara Polygon, in the following the polarimetric elevation models of Figs. 18 and 18 calculated separately for the HV and LR bases plus the polarimetric differential interferograms such as HH - HV and LL - RR, etc., are provided for both the L and C-band data sets.

Fig. 17L L-Band Elevation Model of Selenga Delta Region with Height Profile Extraction within Kudara Polygon
(a. HH b. HV c. VV d. LL e. LR f. RR)

Fig. 17C C-Band Elevation Model of Selenga Delta Region with Height Profile Extraction within Kudara Polygon
(a. HH b. HV c. VV d. LL e. LR f. RR)

From an inspection of these data sets, and those of Peltzer and Rosen of Fig. 16L/C, we observe that there exist at times appreciable differences which might be attributed to directive growth features (major "averaged" alignment of branches, etc.). Furthermore, a comparison of C- versus L-band interferometric data gives reason for wavelength-dependent depth penetration focusing capabilities into forested growth, etc., which also follows from the polarimetric differential interferograms in Figs. 18L/C.

Fig. 18L L-Band Polarimetric Differential Interferograms with selected Height Profiles
(a. HH - VV b. LL - RR)

Fig. 18C C-Band Polarimetric Differential Interferograms with selected Height Profiles
(a. HH - VV b. LL - RR)

The interpretation of the minute differences observed will require more exact groundtruthing such as precise tree/shrub height measurements along selected profile paths within the Kudara Polygon (taking into account meteorological factors such as humidity, wind and rain storm impact directions, etc.). Extension of the selected strip in both backward (SW) and forward (NE) orbital directions of the Tien San tracks 122.20 and 154.20 is also desired in order to cover the entire geo/eco-environmental area of interest to our colleagues of RAS-SD-BNSC at Ulan Ude, Buriatia.

Most ideally, complete year-round (seasonal) POL-D-InSAR monitoring of this Selenga-Delta region and the pertinent Hövsögöl Lake region of neighboring Norch-Central Mongolia should be carried out during the forthcoming spaceborne LIGHT-SAR, ECHO-SAR and EROS missions in addition to a well-selected set of airborne measurement campaigns utilizing the most advanced POL-D-InSAR imaging platforms available such as the upgraded NASA-IPL AIR/TOP-SAR, NAWC-QUAD-SAR, DCRS EMI-SAR, DLR E-SAR, NASDA/CRL POLSAR and the Russian IMARK imaging platform systems which are succinctly described in Kramer [8] for the older versions (before 1995).

CONCLUSIONS

The tremendous utility of air and space-borne polarimetric SAR imaging systems was demonstrated during recent years with the availability primarily of the airborne NASA-JPL AIR/TOP-SAR (P/L/C), NAWC Quadband (UWB: 200MHz - 900MHz, L/C/X), DCRS EMI-SAR (C/X), the DLR E-SAR (P/L/C/X) and the space(shuttle)borne SIR-C/X-SAR missions.

In this paper, the utility of using complete polarimetric, multi-frequency POL-SAR data was not only re-established, but in addition, it was clearly demonstrated that complete polarimetric scattering matrix data are also essential in improving single (dual-polarimetric antenna) systems as well as repeat-pass interferometry. In fact, first cut investigations show that with ultrawideband (multiband and hyper-spectral within 100MHz - 100GHz) POL-D-InSAR systems in addition selective, indepth focussing feature extraction as well as differential directive change identification will be made possible.

By mere coincidence, the SIR-C/X-SAR Mission 2 (94 Oct./08/09 Tien-Shan Tracks 122.20/154.20) provided an ideally matched pair of repeat-pass POLSAR (L/C) images within one of the most sensitive geo/eco-environmental terrestrial regions, the Basin of the Hövsögöl Lake, Mongolia to Baikal Lake, Buriatia containing the tectonically most active Baikal Trench, the Inner-Asian Tectonic Rift Zone, that may separate the Asian continent in the far distant future. Specifically, the Selenga Delta of SE Baikal Lake is one of the most studied tectonically active, and geo/eco-environmentally valuable terrestrial sanctuaries within the heart of the newly dedicated Baikal World Heritage Site. Utilizing the Cloude-Papathanassiou polarimetric-interferometric POL-D-InSAR algorithms together with other polarimetric SAR image feature selection and classification algorithms implemented in this paper, and existing groundtruth data (which both need to be further perfected), we have demonstrated that complete Polarimetric-Interferometric SAR Imaging Systems have to be developed rapidly and that those are far superior to existing single or dual amplitude only polarimetric SAR systems.

Considering the overall integral value of this pilot project, it is suggested and requested that the Hövsögöl-Baikal Lake Basin be selected to become a major future testbed for the SIR-C/X-SAR Mission 3 (SRTM), the US LIGHT&ECHO-SAR, the Japanese EROS and other future fully polarimetric-interferometric POL-D-InSAR space imaging systems. In addition, we suggest that multi-national, multi-institutional airborne POL-D-InSAR measurement campaigns be carried out within the Hövsögöl/Mongolia - to - Baikal/Buriatia region and especially over the 'Kudara Polygon'.

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